AD-A159 427 DETERMINATION OF INSTRUMENT ERRORS BY COMPATIBILITY CHECKING - RESULTS FR..(U) AERONAUTICAL RESEARCH LABS MELBOURNE (AUSTRALIA) R A FEIK SEP 84 ARL-AERO-R-162 1/1

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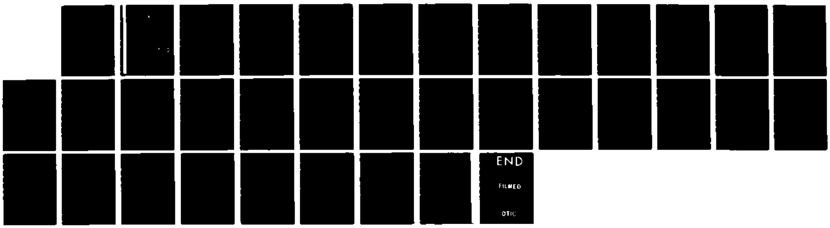

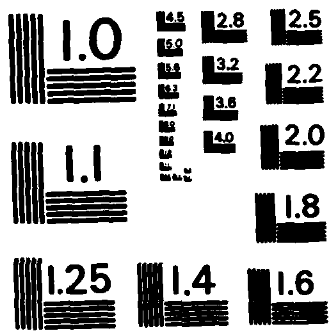

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AR-003-968

DEPARTMENT OF DEFENCE

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AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

AERODYNAMICS REPORT 162

DETERMINATION OF INSTRUMENT ERRORS BY COMPATIBILTY CHECKING— RESULTS FROM DYNAMIC FLIGHT TEST DATA

by

R. A. FEIK

APPROVED FOR PUBLIC RELEASE

COPY No

SEPTEMBER 1984

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DETERMINATION OF INSTRUMENT ERRORS BY COMPATIBILTY CHECKING— RESULTS FROM DYNAMIC FLIGHT TEST DATA

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SUMMARY

The considerable potential benefits of compatibility checking of aircraft dynamic flight data have in the past not been fully realised when applied to real data. It is suggested in this report that this is partly due to the presence of errors in the real data which are not usually accounted for in computer simulation studies. When factors such as accelerometer offset from centre of gravity, measurement time delays and other non-linearities are accounted for, good results can be achieved with moderate quality instrumentation. The effect of these factors on the identified instrument errors are studied in this report and confidence in the results established by a careful comparison with instrument calibrations and expected errors. Other considerations, such as the influence of manoeuvre shape and the inclusion of altitude record, are also discussed, and the conditions for successful application of compatibility checking techniques to flight data are summarised. The importance of understanding the instrumentation system is highlighted.

POSTAL ADDRESS: Director, Aeronautical Research Laboratories,
Box 4331, P.O., Melbourne, Victoria, 3001, Australia

NOTATION

$\mathbf{A}$	Sensitivity matrix, equation (7)
ax, az	Linear accelerations in x, z directions, m. s^{-2}
b_{ax}, b_{az}, b_q etc.	Offset biases in az, az, q etc. measurements
g	Gravitational acceleration, m. s^{-2}
h	Altitude
i	Time index
J	Cost functional to be minimised, equation (5)
N	Number of time points
q	Pitch rate, rad s^{-1}
$\mathbf{R}$	Measurement noise matrix
t	Time, sec
u, w	Velocities in x, z direction
V	Airspeed, m. s^{-1}
x, z	Reference body axes
x_α, z_α	Body axis coordinates of angle of attack probe, *m*
x_a, z_a	Accelerometer position relative to centre of gravity, *m*
α	Angle of attack, rad
Δ	Increment
λ_{ax}, λ_{az}, λ_q etc.	Scale factor error in ax, az, q etc. measurements
ν	Vector of residuals, equation (5)
θ	Pitch attitude, rad
ξ	Parameter vector, equation (4)
σ	Standard deviation

Subscripts

a	Refers to accelerometer location
m	Measured value
out	Output quantity

1. INTRODUCTION

The application of system identification methodology to the extraction of aerodynamic information from flight test data has been of interest to the Aircraft Behaviour Studies–Fixed Wing group at Aeronautical Research Laboratories (ARL) for a number of years. One approach taken, as a first stage in the analysis of the data, has been to make use of redundant information available in the quantities measured in order to identify and remove inconsistencies in the measurements caused by instrument errors. With the instrument errors, such as bias and scale factor change, properly accounted for, excellent agreement between calculated and measured output time histories can be obtained.

Programs for compatibility checking have been reported by a number of authors (Refs 1–8). Work in the Aircraft Behaviour Studies Group was summarised in Ref. 9 and extended further under a Research Agreement with the University of Newcastle (Refs 10, 11). While very satisfactory results using this approach have been obtained with simulated data (Refs 9–11), reported applications to real data obtained during flight tests have not, in general, been very convincing. A possible exception is the work reported in Ref. 3 which uses extremely accurate and expensive instrumentation where expected errors are in any case very small. As instrumentation quality deteriorates, good results become more difficult to achieve but the challenge remains to extract the maximum amount of information from flight tests of limited duration with instrumentation of limited quality, as typically used in flight testing.

A difficulty encountered when applying the method to real data is that, although excellent fits can be achieved between calculated and measured output time histories, the corresponding instrument errors extracted take on unrealistic values. Possible reasons for this include inadequate length of record, neglect of sources of error in the model of the instrumentation system, and possible time delays or shifts in some measurements. In particular, the effects of delay in airspeed measurements and the effects of displacement of instruments from the aircraft centre of gravity are discussed in Ref. 11. Methods for making allowance for accelerometer offsets from the centre of gravity and for determining relative time shifts in measurement channels are reported in a previous note (Ref. 12). Even with these taken into account, the question of credibility of the resulting parameter values remains. Specifically, what level of confidence can be placed in the results and, in particular, can the level be quantified?

The above question can be particularly answered by studying the consistency of results obtained from different flight records and for varying lengths of a given record. Further, the reasonableness of the results can be judged against a knowledge of the instrumentation system and, in particular, from the expected range of errors based on repeated calibrations. This report sets out to establish the credibility of the results using the above considerations, and also suggests a possible quantitative measure of confidence based on the calculated Cramer–Rao bound. In addition, the effect of measurement lags on extracted instrument parameters is documented, and the improvement obtained by including the altitude record as an additional, though noisy, output is studied.

The theoretical formulation of the problem and a brief description of the Maximum Likelihood approach for its solution is discussed in Section 2 of this report. Section 3 considers the test manoeuvres flown and examines the instrumentation and data acquisition system. Results obtained from application of the compatibility checking program to the measured time histories are then presented and analysed in Section 4, and the report concludes with a discussion of some of the possible implications for future flight test investigations.

2. THEORETICAL BACKGROUND

The theoretical formulations of the current approach, based on the aircraft kinematic equations, is summarised in this section and the method of solution using a maximum likelihood technique briefly described.

2.1 Problem Formulation

The flight manoeuvres to be analysed involve only symmetric aircraft motions so that only the longitudinal equations need be considered. The set of non-linear kinematic equations relating aircraft displacements, velocities and accelerations with reference to flat earth axes and written in a body axis system (x, z) fixed in the aircraft are as follows:

$$\left.\begin{aligned} \dot{u} &= -qw+ax_a+q^2x_a-\dot{q}z_a-g\sin\theta \\ \dot{w} &= qu+az_a+\dot{q}x_a+q^2z_a+g\cos\theta \\ \dot{\theta} &= q \\ \dot{h} &= u\sin\theta-w\cos\theta \end{aligned}\right\} \qquad (1)$$

where

u, w are linear velocities in the x, z directions

θ, q are pitch attitude and angular rate

ax_a, az_a are accelerations in the x, z directions at the accelerometer locations

x_a, z_a are accelerometer coordinates relative to the aircraft centre of gravity

g is the gravitational constant.

The set of equations (1) take into account possible offset of the accelerometers from the aircraft centre of gravity (x_a, z_a). For further details see Ref. 12.

In applying the compatibility checking method, values of ax_a, az_a and q are treated as inputs. Measured values of these quantities, taken to be free of random noise, are assumed to be subject to systematic bias and scale factor errors modelled as follows:

$$ax_a = (1+\lambda_{ax})\,ax_m+b_{ax} \qquad (2)$$

with similar equations for az_a and q. In equation (2) λ_{ax} represents the scale factor error and b_{ax} the bias error which relate the measured quantity, ax_m, to the true value ax_a. Substitution of equation (2) into equation (1) yields a set of non-linear equations with scale factors and biases as unknown parameters. The exactness of the kinematic equations and the assumption of no noise on the measured inputs means that the state equations are free of process noise and an estimate for the state is obtained by simple integration.

The outputs, obtained from the state, with allowance for possible scale factor and bias errors are calculated as follows:

$$\left.\begin{aligned} V_{out} &= (1+\lambda_V)(u^2+w^2)^{1/2}+b_V \\ \alpha_{out} &= (1+\lambda_\alpha)\tan^{-1}[(w-qx_\alpha)/u]+b_\alpha \\ \theta_{out} &= (1+\lambda_\theta)\,\theta+b_\theta \\ h_{out} &= (1+\lambda_h)\,h+b_h \end{aligned}\right\} \qquad (3)$$

where the λ's represent scale factor errors and the b's are bias errors while x_α (assumed known) represents the distance of the angle of attack sensor ahead of the centre of gravity. The biases and scale factors in equations (2) and (3) are estimated by optimising the match between the output and the noisy measurements. The full set of parameters estimated also includes the initial conditions of the state. The only exception is $h(o)$ which is obtained by an average over the first second of record. Consequently, the h equation is only used to calculate perturbations about $h(o)$, and b_h can be assumed to be zero. The full parameter vector to be considered is thus,

$$\begin{aligned}\xi = [&\lambda_{ax},\ b_{ax},\ \lambda_{az},\ b_{az},\ \lambda_q,\ b_q,\ \lambda_V,\ b_V,\ \lambda_\alpha,\ b_\alpha, \\ &\lambda_\theta,\ b_\theta,\ \lambda_h,\ u(o),\ w(o),\ \theta(o),\ x_a,\ z_a]^T \end{aligned} \tag{4}$$

2.2 Maximum Likelihood Solution

The maximum likelihood estimator sets out to find the set of parameters (Equation (4)) for which the measured values of the outputs would be the most likely to occur. Ref. 11 shows that this is equivalent to minimisation of the cost functional,

$$J(\xi, \mathbf{R}) = \frac{1}{2} N \log |\mathbf{R}| + \frac{1}{2} \sum_{i=1}^{N} \nu^T(i)\, \mathbf{R}^{-1}\, \nu(i) \tag{5}$$

where $\nu(i)$ is the vector of residuals, i.e. the difference between measured and predicted output, and $\mathbf{R}$ is a weighting covariance matrix. An estimate for $\mathbf{R}$ is given by:

$$\hat{\mathbf{R}} = \frac{1}{N} \sum_{i=1}^{N} \nu(i)\, \nu^T(i). \tag{6}$$

With $\mathbf{R}$ given by equation (6), equation (5) is minimised with respect to ξ using a modified Newton–Raphson technique, and the procedure iterated until convergence. For zero mean, independent, Gaussian measurement noise the final estimates are unbiased and efficient, i.e. the covariance of the estimates is given by the Cramer–Rao lower bound,

$$\text{covariance } \{\xi\} = \left[\sum_{i=1}^{N} \mathbf{A}^T(i)\, \hat{\mathbf{R}}^{-1}\, \mathbf{A}(i) \right]^{-1} \tag{7}$$

where the elements of the sensitivity matrix, $\mathbf{A}$, are the partial derivatives of the elements of the calculated output vector (equation (3)) with respect to the elements of the parameter vector, ξ (equation (4)). Thus for 18 parameters and 4 outputs, $\mathbf{A}$ is a 4 by 18 matrix. Details relating to the calculation of the sensitivity matrix for the specific problem under consideration are set out in Ref. 12.

3. FLIGHT TRIALS AND DATA ACQUISITION

This section describes the flight manoeuvres under examination and discusses the instrumentation and data acquisition procedures. In particular, instrumentation calibrations are examined in some detail with the object of assessing the range of systematic errors which may be reasonably expected.

3.1 Manoeuvre Description and Instrumentation

Flight data were obtained on an opportunity basis during a performance flight test program being undertaken by the RAAF Aircraft Research and Development Unit (ARDU) at Edinburgh, South Australia. The manoeuvre specified for the current investigation was a roller-coaster type involving sequences of gradual pull-ups and push-overs. Initially, relatively short test durations (10–20 seconds) were specified but subsequent analysis indicated that longer records were required in order to obtain reliable results. Two manoeuvres provided total record lengths of 40 seconds or longer and these were chosen for detailed analysis. The basic features of the manoeuvres are summarised in Table 1 and time histories are shown plotted in Figures 1 and 2.

TABLE 1

Manoeuvre Details

	Manoeuvre 1	Manoeuvre 2
Nominal Mach No.	0·65	0·87
Nominal Altitude, ft	33,000	33,000
ax range, m/s²	0·64–1·24 ($\pm$0·05)	0·07–0·99 ($\pm$0·05)
az range, m/s²	−19·1–2·5 ($\pm$0·05)	−15·3–0·58 ($\pm$0·05)
q range, rad/s	−0·16–0·17 ($\pm$0·002)	−0·022–0·067 ($\pm$0·002)
V range, m/s	178–209 ($\pm$1)	261–283 ($\pm$1)
α range, rad	0–0·20 ($\pm$0·002)	0·012–0·13 ($\pm$0·002)
θ range, rad	−0·37–0·34 ($\pm$0·002)	−0·17–0·17 ($\pm$0·002)
h range, m	9489–10,204 ($\pm$8)	9780–10,130 ($\pm$8)

Flight test instrumentation included a pitch rate gyro, pitch attitude gyro and accelerometers to measure normal and longitudinal accelerations. In addition true airspeed and altitude were recorded from the Air Data Computer. Finally, angle of attack was measured using a specially designed nose probe fitted with a hemispherical head 5 port flow angle sensor. This probe was attached to the standard air data probe fitted to the aircraft.

Figure 1 shows the input (ax, az and q) and output (V, α, θ, h) time histories for Manoeuvre 1 at a nominal Mach Number of 0·65 and altitude of 33 000 ft, while Figure 2 shows the same information for Manoeuvre 2 at Mach Number 0·87 and altitude 33 000 ft. The oscillatory nature of the time histories in Figure 1, particularly for q and az, is due to the aircraft pitch dampers being turned off during this manoeuvre. By contrast most of Manoeuvre 2 was flown

with dampers on resulting in much smoother records until approximately 41 seconds when the dampers were disengaged. For compatibility checking purposes the presence or absence of dampers appeared to make very little difference but the short period information available in Figure 1 may be useful in any subsequent analysis, particularly if stability derivatives are of interest.

The ranges spanned by the input and output variables in the course of the manoeuvres (Table 1) indicate that Manoeuvre 1 is a somewhat more aggressive manoeuvre. For example, the peak to peak difference in normal acceleration is almost 22 m/s^2 for Manoeuvre 1 and only 16 m/s^2 for Manoeuvre 2. For pitch rates the ranges are 0·33 rad/s and 0·09 rad/s respectively and for pitch attitude 0·71 rad and 0·34 rad respectively. Despite this, the longitudinal acceleration, ax, changes by a greater amount in Manoeuvre 2 (1·06 m/s^2) than in Manoeuvre 1 (0·60 m/s^2). Both these values are rather small and some attempt to increase longitudinal acceleration may be worthwhile if longitudinal parameters are of particular interest. Also shown in Table 1 (in brackets) are estimated 'noise' levels on the measurements, based on noise apparent on the records. These are useful for making initial estimates of the **R** matrix in the cost functional, equation (5).

3.2 Preprocessing

Flight data were digitally recorded on magnetic tape (12 bit accuracy, 60 samples per second) using ARDU's Aircraft Flight Test Recording and Analysis System (AFTRAS—Ref. 14). Seven track copies of the flight tapes provided to ARL were processed as described in Ref. 15 to provide time histories of the chosen channels in engineering units. Calibration data required for the conversions were obtained by ARDU for most channels and the information provided on the tapes. The only exception was the flow-angle sensor calibrations which were determined in the ARL transonic wind tunnel.

Pitch acceleration, $\dot{q}$, required for accelerometer offset corrections (Eqn 1) was calculated by numerical differentiation of the pitch rate records using a recursive least squares algorithm as described in Ref. 12. This provided satisfactory $\dot{q}$ time histories which are included among the plots in Figures 1 and 2. Accelerometer offsets from the centre of gravity, estimated for given fuel state, were x_a equal to $-0{\cdot}11$ m and $-0{\cdot}12$ m for Manoeuvres 1 and 2 respectively and z_a equal to 0·53 m for both cases.

Finally, prior to application of the compatibility checking program, relative phase shifts in the measurement channels were determined as described in Ref. 12 and time histories shifted appropriately to bring them into correct alignment. The relative time shifts (delays) for ax, az, q V, α and θ were (in units of 1/60 second) 6, 12, 6, 28, 3, 8 respectively. A value of 28 was also assumed for the altitude, h, channel. The effects of variations from these reference values on the identified parameters will be considered in Section 4.

3.3 Calibrations

A careful evaluation of instrument calibrations provided by ARDU was made in order to assess which parameters needed to be retained in the parameter vector and the possible range of values which they may be expected to take. This assessment was based on repeat calibrations which were performed over the two or three months during which the main trials were in progress. It is assumed that changes in the calibrations are an indication of bias and scale factor errors which can be expected.

The range of values spanned by the calibrations is shown in Figures 3 to 7, and Table 2 summarises the maximum variations in slope obtained. The figures also indicate the range covered by respective measurements during the trials. At mid-range a shift can be specified which would make the calibration curves agree at that point, and is an indication of the bias likely to be identified if no adjustment slope were permitted. This figure is also given in Table 2.

TABLE 2

Maximum Slope and Bias Errors

Measurement	Slope variation, %	Bias
acceleration, *az*	4·3	3 m/s²
pitch rate, *q*	26·4	0·02 rad/s
airspeed, *V*	1·2	10 m/s
pitch attitude, θ	11·7	0·07 rad
altitude, *h*	29·3	—

The slope variation and bias for *az* indicated in Table 2 appear to be excessive considering the accuracy generally expected of accelerometers. Similar variations were not found in the *ax* and *ay* accelerometers. For example, in repeat calibrations of the *ay* accelerometer the slope changed by only 0·3% and the mid-range shift, or bias, was less than 0·01 m/s². It is concluded that the *az* accelerometer readings are likely to be subject to uncharacteristically large errors. Nevertheless, inspection of Figure 3 shows that, over the relatively small range covered in the trials, a simple shift is sufficient to bring the two curves into reasonable agreement. Ignoring the slope change will lead to an error of 0·4 m/s² maximum at the extremities of the range.

The pitch rate gyro calibrations show a very large slope change which cannot be ignored over the range covered in the trials. The slope discrepancy was brought to light by calibrations using different calibration equipment and suggests that at least one of the turntables used produced erroneous results. Because of this both bias and scale factor errors have to be represented in the compatibility checking process. Similarly, fairly large scale factor errors can be anticipated in the pitch attitude measurements (Fig. 6).

The airspeed calibrations (Fig. 5) show a very small change in slope but large bias errors appear possible. On the other hand the altitude calibrations in Figure 7 imply the possibility of large slope errors. Both airspeed and altitude measurements may be subject to position errors which are functions of Mach number (M), due for example to changing interference patterns with M between the standard aircraft probe and the adjacent hemispherical probe. Curves for pressure error correction (PEC) to altitude were supplied by ARDU and are shown in Figure 8. For manoeuvre 1 centred at $M = 0{\cdot}65$ the pressure error correction is relatively small and does not vary greatly with M. At most, the approximately linear variation between $M = 0{\cdot}6$ and $0{\cdot}7$ would appear as an apparent slope error, λ_h, in the altitude calibration. On the other hand, for manoeuvre 2, centred at $M = 0{\cdot}87$, the correction may be quite large and varies non-linearly with M. The effects of neglecting pressure error corrections may be significant in this case and will be considered further in the next section. An equivalent correction curve for airspeed was unfortunately not provided but, assuming that static pressure errors can be related to airspeed errors through the compressible Bernouilli equation, a correction curve can be inferred and will have broadly similar characteristics to the curve in Figure 8.

The angle of attack sensor was calibrated in the ARL transonic wind tunnel and no attempt was made at in-flight calibrations. Consequently, large zero offsets can, in general, be expected due to flow upwash effects ahead of the aircraft. Similarly, it cannot be assumed that the slope of the calibration curve will be the same in flight as in the wind tunnel.

In summary, consideration of instrumentation calibrations has provided some feel for the magnitude of bias and scale factor errors to be expected. In particular, it is clear that scale factor

errors can be significant in many of the channels and must be accounted for. Only λ_{ax} and λ_{az} can be neglected with some confidence. Table 2 suggests that λ_V is also likely to be small, but the effects of pressure error correction especially over the Mach number range of manoeuvre 2 suggests that λ_V must be retained, at least for that case.

4. RESULTS

In this section the results from application of the compatibility checking program to the flight data are presented and discussed. The unknown parameter vector (Eqn 4) in general contained all possible bias and scale factor errors with the exception of λ_{ax} and λ_{az} as discussed in the previous section. Initial conditions were also identified but the effects of accelerometer offsets x_a, z_a were found to be negligible due to the relatively mild manoeuvres, and consequently they have been excluded from the parameter vector. Initial values for the elements of the weighting matrix **R** were based on the measurement 'noise' levels of Table 1, i.e. the diagonal elements were set equal to the square of the appropriate 'noise' level. The complete set of measurements (Eqn 3) was used in general. Typical CPU time on the DECsystem-10 was about 65 minutes for 10 iterations with a record length of 40 seconds.

4.1 Manoeuvre 1 Results

These are summarised in Tables 3 and 4 and include the effects of variation in record length, changes in parameter vector and measurement vector, and relative measurement time shifts, to be discussed in turn below. Following this, the scatter in results will be examined in closer detail.

4.1.1 Record Length

The first three runs in Table 3 compare the results obtained with record lengths of 40, 50 and 60 seconds respectively. In all cases excellent matches were obtained with the measured and calculated output histories being almost indistinguishable. The identified parameter values are very consistant, with the possible exception of b_V and $u(o)$ which show significant change with increasing record length. At the same time, the estimated standard deviations for b_V and $u(o)$ show some decrease. The scale factor errors λ_V, λ_α and λ_θ although showing some variation with record length are in all cases small. The rms fit errors are also in reasonable agreement with the 'noise' on the measurements as given in Table 1.

4.1.2 Change in Parameter and Measurement Vectors

Because of the small values obtained for λ_V, λ_α and λ_θ in 4.1.1 some computer runs were carried out with their values set to zero. The reduction in the number of parameters to be extracted not only leads to a reduction in CPU time but eases the demands on the identification algorithm thereby leading to improvements in the standard deviations of the estimates as shown in runs 4 and 5 of Table 3. This is particularly true for b_V, $u(o)$ and λ_θ compared with runs 1 to 3. At the same time general consistency in results for record lengths of 40 seconds (Run 4) and 60 seconds (Run 5) is further improved.

TABLE 3

Results from Manoeuvre 1

Estimated standard deviations in parentheses

Parameter	RUN NUMBER					
	1	2	3	4	5	6
b_{ax}, m/s^2	−0·204(0·0034)	−0·148(0·0033)	−0·118(0·0034)	−0·184(0·0036)	−0·131(0·0033)	0·554(0·0064)
b_{az}, m/s^2	−1·103(0·0012)	−1·133(0·00080)	−1·156(0·00081)	−1·112(0·0014)	−1·151(0·00087)	−1·114(0·0010)
λ_q	−0·234(0·00071)	−0·214(0·00059)	−0·184(0·00060)	−0·204(0·00019)	−0·205(0·00020)	−0·206(0·00020)
b_q, rad/s	−0·027(0·00002)	−0·027(0·00002)	−0·28(0·00002)	−0·028(0·00001)	−0·028(0·00001)	−0·028(0·00001)
λ_V	0·041(0·0012)	0·016(0·0011)	−0·026(0·0010)	—	—	—
b_V, m/s	−18·29 (0·360)	−7·36 (0·295)	8·88 (0·274)	−3·18 (0·084)	−1·36 (0·104)	−2·99 (0·086)
λ_α	0·059(0·0011)	0·037(0·00093)	0·013(0·0011)	—	—	—
b_α, rad	0·060(0·00039)	0·055(0·00034)	0·053(0·00034)	0·063(0·00039)	0·055(0·00032)	0·054(0·00032)
λ_θ	0·036(0·00098)	0·011(0·00079)	−0·028(0·00077)	—	—	—
b_θ, rad	−0·032(0·00039)	−0·038(0·00034)	−0·038(0·00033)	−0·031(0·00040)	−0·040(0·00033)	−0·108(0·00065)
λ_h	−0·110(0·0013)	−0·108(0·0013)	−0·106(0·0012)	−0·111(0·0013)	−0·104(0·0012)	—
$u(o)$, m/s	211·25 (0·175)	205·89 (0·139)	198·12 (0·140)	204·72 (0·085)	203·25 (0·103)	204·74 (0·085)
$w(o)$, m/s	16·30 (0·079)	17·50 (0·067)	18·21 (0·069)	16·12 (0·082)	18·46 (0·069)	19·76 (0·066)
$\theta(o)$, rad	0·117(0·00039)	0·125(0·00034)	0·133(0·00035)	0·120(0·00041)	0·130(0·00034)	0·199(0·00065)
rms(V)	0·5947	0·5865	0·5837	0·5947	0·5862	0·5683
rms(α)	0·001859	0·002016	0·003725	0·002469	0·004538	0·03278
rms(θ)	0·002188	0·002153	0·002941	0·002244	0·002978	0·002960
rms(h)	15·02	16·89	15·82	14·96	15·83	—
Length, s	40	50	60	40	60	60
N	2400	3000	3600	2400	3600	3600

TABLE 4

Results from Manoeuvre 1 (continued)

Record Length = 60 sec., $N = 3600$

Estimated standard deviations in parentheses

Parameter	RUN NUMBER			
	5	7	8	9
b_{ax}, m/s²	−0·131(0·0033)	−0·105(0·0033)	*−0·033(0·0033)*	*0·098(0·0036)*
b_{az}, m/s²	−1·151(0·00087)	−1·157(0·00094)	−1·156(0·00098)	−1·145(0·00095)
λ_q	−0·205(0·00020)	−0·205(0·00020)	−0·209(0·00021)	−0·206(0·00020)
b_q, rad/s	−0·028(0·00001)	−0·028(0·00001)	−0·028(0·00001)	−0·028(0·00001)
λ_V	—	—	—	—
b_V, m/s	−1·36 (0·104)	−1·40 (0·103)	−2·16 (0·107)	−1·50 (0·102)
λ_α	—	—	—	—
b_α, rad	0·055(0·00032)	0·056(0·00033)	0·053(0·00033)	*0·036(0·00035)*
λ_θ	—	—	—	—
b_θ, rad	−0·040(0·00033)	−0·042(0·00033)	−0·046(0·00033)	−0·062(0·00036)
λ_h	−0·104(0·0012)	—	—	—
$u(o)$, m/s	203·25(0·103)	203·27 (0·102)	203·82 (0·106)	202·60 (0·101)
$w(o)$, m/s	18·46 (0·069)	18·49 (0·070)	19·36 (0·071)	*22·49 (0·074)*
$\theta(o)$, rad	0·130(0·00034)	0·133(0·00035)	0·136(0·00035)	*0·153(0·00037)*
rms(V)	0·5862	0·5816	0·6018	0·6470
rms(α)	0·004538	0·004448	0·004653	0·004335
rms(θ)	0·002978	0·002990	0·003021	0·002968
rms(h)	15·83	27·66	27·81	27·95
az shift	12	12	0	12
V shift	28	28	28	52

The effect of removing the altitude history from the records to be matched is shown in run 6 of Table 3. Comparison of run 6 with run 5 shows that the principal difference is significant change in the values of $\theta(o)$, b_θ and b_{ax} together with a deterioration in their accuracy as indicated by the estimated standard deviations. This result is not surprising since altitude changes imply considerable information about θ which in turn influences ax, as can be seen on examination of the first and last of equations (1). Consequently even relatively inaccurate measurement of altitude provides valuable information for several parameters which may be of interest. The inclusion of altitude record is worthwhile even if significant scale factor error, λ_h, is uncorrected. This can be seen in Table 4 by comparing run 7, where λ_h is fixed at zero, with run 5 (repeated from Table 3).

4.1.3 Time Shifts

Runs 8 and 9 in Table 4 demonstrate the effects of relative time shifts (delays) in the az and V records showing the errors likely to be introduced if time shifts have not been accounted for correctly. In particular, the method used to determine time shifts in the records (Ref. 12), is least accurate for az and V shifts. In run 8 the az shift (delay) is changed from 12 units (i.e. 12/60 seconds) to 0 units. Thus instead of lagging the q record by 0·1 second it now leads by the same amount. The only significant change is in b_{ax} which has changed to −0·033 from −0·105 in run 7. As expected there is also some deterioration in the rms fit errors, particularly in the α record. In run 9 the V delay has been increased from 28 units to 52 units, i.e. 22/60 second to 46/60 second with respect to the q record. Several parameters, shown underlined, have suffered significant changes compared to run 7. Of most concern is the large effect on b_α, since accurate records of α are likely to be of importance in any subsequent analysis. The expected deterioration in the rms fit for V is also apparent. These results show the importance of accounting for time shift in airspeed measurements particularly in view of the large value it commonly takes.

4.1.4 Scatter of Results

Figure 9 summarises graphically the scatter in the extracted values of several parameters as obtained in runs 1 to 5 (Table 3). The scatter band is compared (in brackets) with the largest estimated standard deviation, multiplied by a factor of 20, from Table 3. In general this provides a reasonable estimate of the scatter, with the exception of λ_h where the scatter would be over-estimated by a factor of 7 or 8. In part justification of the factor of 20 it should be noted that neglect of process noise in the maximum likelihood algorithm was found, in Ref. 16 using simulated data, to lead to an underestimate of the scatter by a factor of approximately 3 to 5 depending on noise levels. With real data, a further underestimation can be expected associated with the limited bandwidth of the measurement noises. This effect is discussed in detail in Ref. 17, which reports a typical empirical factor of 5–10 required to bring the estimated standard deviations into line with the observed scatter of the parameter estimates. These two effects combine to give the present factor of about 20 on the estimated standard deviations required to produce a reasonable indication of the level of confidence in the results.

Looking more closely at the identified errors λ_V and b_V in the airspeed calibrations, Figure 10 plots the relation between measured and true airspeeds as implied by the values of λ_V and b_V obtained in runs 1, 2, 3 and 5 (Table 3). Thus, although the scatter in b_V is about $\pm$ 14 m/s (Fig. 9) the actual scatter in airspeed over the range covered in the trials is somewhat less at around $\pm$ 8 m/s (see also $u(o)$ in Figure 9).

TABLE 5

Results from Manoeuvre 2

Record Length = 50 sec., N = 3000

Estimated standard deviations in parentheses

Parameter	RUN NUMBER			
	1	2	3	4
b_{ax}, m/s^2	−0·173(0·0032)	−0·169(0·0031)	−0·224(0·0034)	−0·217(0·0031)
b_{az}, m/s^2	−1·143(0·00085)	−1·135(0·00090)	−1·141(0·00085)	−1·153(0·00081)
λ_q	−0·161(0·00051)	−0·204(0·00030)	−0·200(0·00050)	−0·201(0·00050)
b_q, rad/s	−0·025(0·00002)	−0·024(0·00001)	−0·024(0·00002)	−0·024(0·00002)
λ_v	0·402(0·0013)	0·461(0·0012)	0·080(0·0011)	0·083(0·0011)
b_v, m/s	−97·62 (0·37)	−134·3 (0·35)	−30·20 (0·32)	−31·23 (0·31)
λ_α	−0·075(0·00088)	—	−0·030(0·00091)	−0·031(0·00091)
b_α, rad	0·051(0·00030)	0·048(0·00031)	0·054(0·00032)	0·054(0·00030)
λ_θ	−0·044(0·00075)	—	0·003(0·00080)	0·005(0·00080)
b_θ, rad	0·0098(0·00031)	0·0082(0·00032)	0·013(0·00034)	0·012(0·00032)
λ_h	−0·340(0·0020)	−0·343(0·0022)	−0·339(0·0022)	0·343(0·0025)
$u(o)$, m/s	260·39 (0·161)	274·18 (0·129)	273·53 (0·174)	273·53 (0·173)
$w(o)$, m/s	7·45 (0·084)	7·90 (0·087)	6·58 (0·092)	6·47 (0·086)
$\theta(o)$, rad	0·007(0·00033)	0·008(0·00033)	0·003(0·00035)	0·003(0·00032)
rms(V)	0·6250	0·6166	0·5144	0·4999
rms(α)	0·001087	0·001293	0·001501	0·001056
rms(θ)	0·002248	0·002333	0·002248	0·002298
rms(h)	15·01	14·86	15·06	16·14
PEC	—	—	*V*	*V, h*

4.2 Manoeuvre 2 Results

The results for manoeuvre 2, all of which relate to a record length of 50 seconds, are summarised in Table 5. In run 1 all the relevant parameters were identified but pressure error corrections (PEC), discussed in 3.3 were not applied. The results are in general consistent with those obtained from manoeuvre 1, taking into account the possible range of calibration errors previously discussed. The most notable exceptions are λ_v and b_v which take on very large values, but combine with one another in such a way that, over the range of interest, the calculated airspeed magnitudes are not very different from those measured. Nevertheless, these large values point to the possibility of some unmodelled factor in the airspeed calibration.

The effect of neglecting λ_α and λ_θ, which, although larger than for manoeuvre 1, are still relatively small, is shown in the run 2 results of Table 5. In general there is little change compared with run 1 results. Some improvement in the estimated standard deviations of λ_q and $u(o)$ is apparent and the values of these parameters also change slightly, together with a more notable change in the values of λ_v and b_v.

The remaining columns in Table 5 show the effects of including pressure error corrections (PEC) in the airspeed record (run 3) and also the altitude record (run 4) as described in 3.3. The most significant effect in run 3 is the large change in the values of λ_v and b_v which now take on much smaller values than previously. This, together with the improvement in the airspeed rms fit error, indicates the importance of making allowance for the non-linear PEC at transonic Mach numbers. Parameters other than λ_v and b_v are, fortunately, only slightly changed. Finally, the inclusion of PEC in the altitude measurements influences only λ_h in any significant way. The value of λ_h in run 3 has reversed sign in run 4 suggesting the possibility of an overcorrection.

4.3 Summary of Results

A summary of the results of this investigation, including a comparison of manoeuvre 1 and manoeuvre 2 parameters, is shown in Table 6. The values are selected from Tables 3 and 5 and correspond broadly to the lowest estimated standard deviations and thus represent the values with the highest level of confidence. The error ranges indicated in Table 6 are in fact 20 times the

TABLE 6

Summary of Extracted Parameters

Parameter	Manoeuvre 1	Manoeuvre 2
b_{ax}, m/s^2	$-0\cdot13\pm0\cdot07$	$-0\cdot17\pm0\cdot07$
b_{az}, m/s^2	$-1\cdot15\pm0\cdot02$	$-1\cdot14\pm0\cdot02$
λ_q	$-0\cdot21\pm0\cdot004$	$-0\cdot20\pm0\cdot006$
b_q, rad/s	$-0\cdot028\pm0\cdot0002$	$-0\cdot024\pm0\cdot002$
λ_v	$-0\cdot026\pm0\cdot02$	—
b_v, m/s	$-1\cdot4\pm2$	—
λ_α	$0\cdot013\pm0\cdot02$	$-0\cdot075\pm0\cdot02$
b_α, rad	$0\cdot055\pm0\cdot006$	$0\cdot050\pm0\cdot006$
λ_θ	$-0\cdot028\pm0\cdot02$	$-0\cdot044\pm0\cdot02$
b_θ, rad	$-0\cdot04\pm0\cdot007$	$0\cdot010\pm0\cdot006$
λ_h	$-0\cdot10\pm0\cdot02$	—
$u(o)$, m/s	204 ± 2	274 ± 3
$w(o)$, m/s	$18\cdot4\pm1$	$7\cdot5\pm2$
$\theta(o)$, m/s	$0\cdot13\pm0\cdot007$	$0\cdot007\pm0\cdot007$

estimated standard deviations, as discussed in 4.1.4. Despite the differences in the two manoeuvres the error confidence bands are very similar.

The parameter values obtained are also very consistent between the two manoeuvres, with the exception of b_θ and leaving out the airspeed and height parameters in manoeuvre 2, which are affected by significant pressure error corrections, as discussed in 4.2. Comparison of the confidence bands with extracted parameter values leads to the following observations.:

(*a*) Several parameters, e.g. b_{az}, λ_q, b_q are significantly different from zero and very accurately determined.

(*b*) The parameters b_{ax}, b_α and b_θ appear to be reasonably accurately determined and also non-zero. In particular b_α indicates a bias error of close to 3° in angle of attack measurements. However, note the effect of time shift in the V measurement on these parameters (4.1.3).

(*c*) b_V, λ_V, λ_α and λ_θ in manoeuvre 1 are not significantly different from zero. Consequently, the error in V measurement is not significantly different from zero. In particular the initial airspeed $(u^2(o)+w^2(o))^{1/2} \approx 204 \cdot 8$ m/s compares with the measured initial airspeed of $202 \cdot 6$ m/s. As a matter of interest, the respective values for manoeuvre 2 are $274 \cdot 1$ m/s and $267 \cdot 1$ m/s, but PEC complicates the comparison in this case.

Finally, it is notable that the extracted parameter values in Table 6 are consistent with the possible calibration errors discussed in 3.3. In particular, the large values of b_{az} and λ_q confirm the calibration difficulties encountered with the respective transducers, which are not normally expected to be subject to large error.

5. CONCLUDING REMARKS

The application of compatibility checking techniques to dynamic flight data measurements, as described in this report, has the potential to address a range of problems which may arise when trying to extract aerodynamic information from flight data. For example, while stability and control testing usually only requires measurement of perturbations relative to some reference state, there are occasions when absolute measurement accuracies are required over a wide range of operating conditions, e.g. Drag as a function of angle of attack in performance testing. In other cases measurements may be so inaccurate as to be unusable, e.g. airspeed and angles of attack and sideslip in a spinning manoeuvre. The possibility of reconstructing these from accurate (corrected) inertial measurements is very attractive. Again, when linear representation of the aerodynamic forces and moments as functions of the independent variables, via the aerodynamic derivatives, is not possible, as in high angle of attack manoeuvres, it may be more desirable to obtain the absolute values of the forces, moments and independent variables and, as a second stage, seek to establish the functional relationship.

Compatibility checking opens up the possibility of analysing data effectively in all these circumstances and successful implementation of this approach to real data offers great potential benefits. A previous report considered factors likely to arise in flight data and not usually considered in computer simulation studies. These factors, such as accelerometer offset from the centre of gravity, measurement time delays and so on can have considerable impact on the results, and methods were devised to take them into account in the compatibility checking process. The current report follows on by looking in detail at the identified instrument parameters and attempting to establish a degree of confidence in the values obtained. This has been achieved, partly by a careful study of the characteristics of the instrumentation system and calibration curves, thereby establishing a possible range of errors, followed by a comparison of the identified errors with this expected range. Secondly, the consistency of the results from the two flight records

analysed and from varying record lengths, has added to the overall confidence. Further, the Cramer–Rao bound, multiplied by a factor of 20, appears to give a reasonable quantitative measure of the scatter of the results and can be used as an indication of the accuracy with which individual parameters are extracted.

In order to obtain consistent results for all parameters, particularly airspeed errors, it has been found necessary to use record lengths of the order of 40 seconds or more. This contrasts with typical record lengths of 5 to 10 seconds for stability and control testing. At the same time, the altitude record, even though subject to fairly large systematic and random errors, was found to contain information useful for coping with the correlation between some parameters, namely b_{ax}, b_θ and $\theta(o)$. The present study has brought out the importance of understanding the instrumentation system and of making allowance for sources of error other than simple bias and scale factor. As well as accounting for centre of gravity offset and measurement time delays, particularly in airspeed, this report has considered the effects of airspeed and altitude pressure error corrections which introduce significant non-linearities for Mach numbers in the transonic range. The important effect which delay in the airspeed measurement has on several parameters suggests that it may be worth putting some effort into attempting to model the delay, perhaps as a simple first order lag, and then identify it as an additional parameter.

The two manoeuvres analysed differed significantly in the amount of short period dynamics present but, so far as the compatibility checking algorithm was concerned, no differences were found in identifying the systematic errors. Hence the manoeuvre shape can be chosen to reflect the overall aims of the flight trials. For example, for performance testing, a smooth (small pitch rate) roller coaster type of manoeuvre covering a wide angle of attack range with relatively large longitudinal accelerations may be desirable. On the other hand, for stability and control information, larger excursions in angular rates would be required. Since simple pulse or doublet responses are no longer essential, the opportunity exists to separate out linear acceleration and rate derivatives. For centre of gravity determination accurate results would only be obtained with a fairly vigorous (high pitch acceleration) manoeuvre. This has yet to be tested with flight data. A combination of several types of manoeuvre types may be devised to suit the purpose at hand. Clearly the availability of compatibility checking procedures raises a number of new aspects for consideration when planning flight trials. The current study indicates that, with proper care and planning, compatibility checking can be applied with success to flight data obtained with moderate quality instrumentation.

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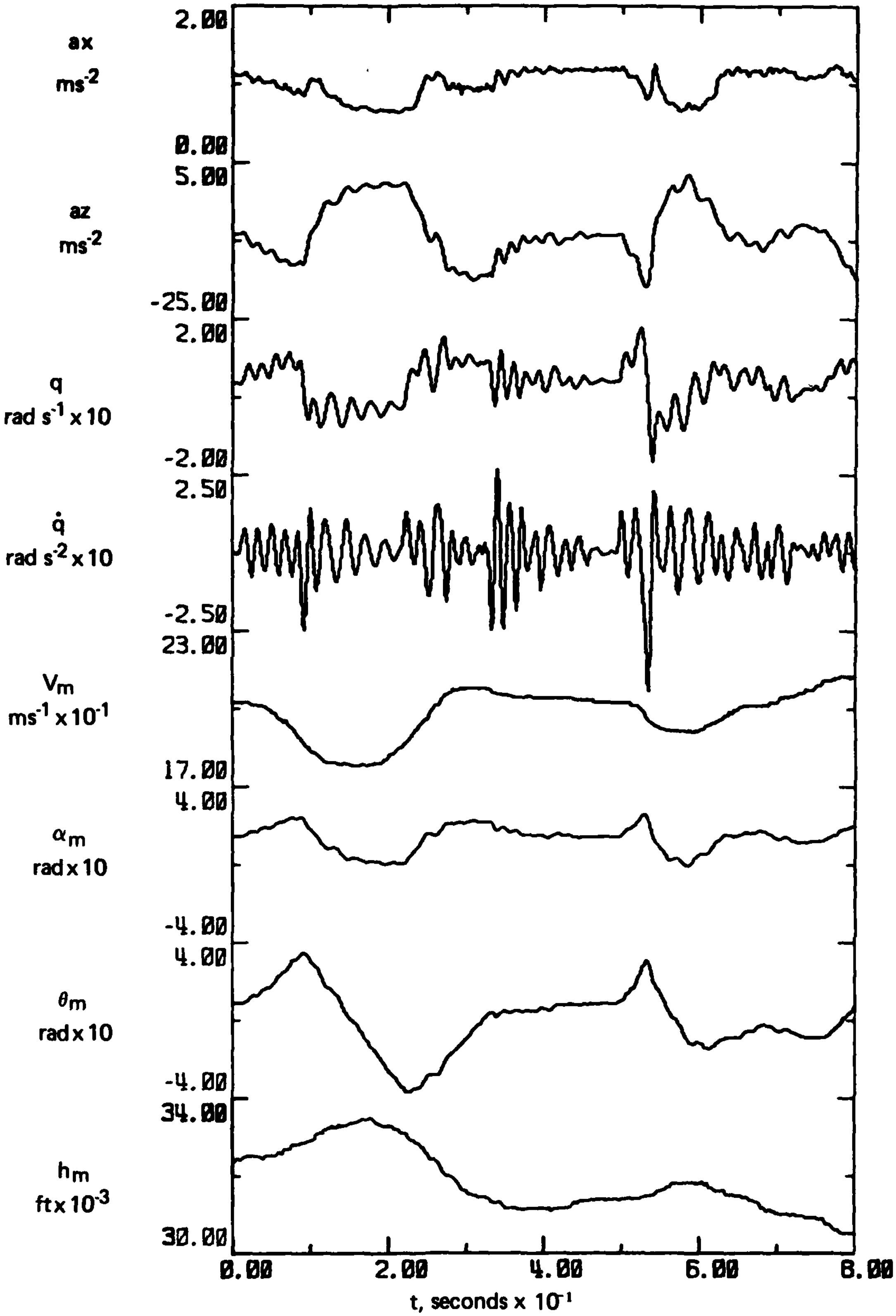

FIG. 1 MANOEUVRE 1 TIME HISTORIES, M = 0.65, h = 33000 ft.

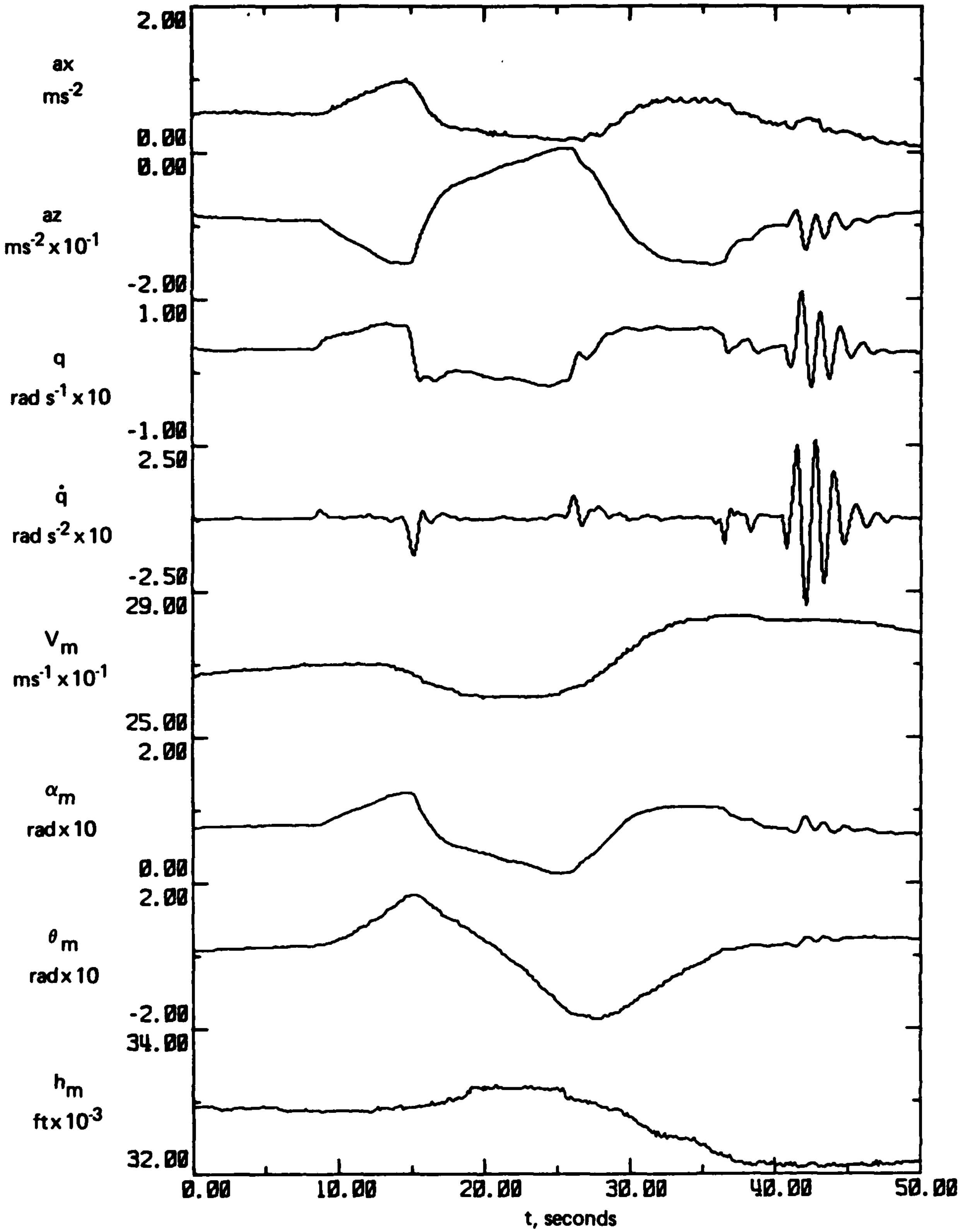

FIG. 2 MANOEUVRE 2 TIME HISTORIES, M = 0.87, h = 33000 ft.

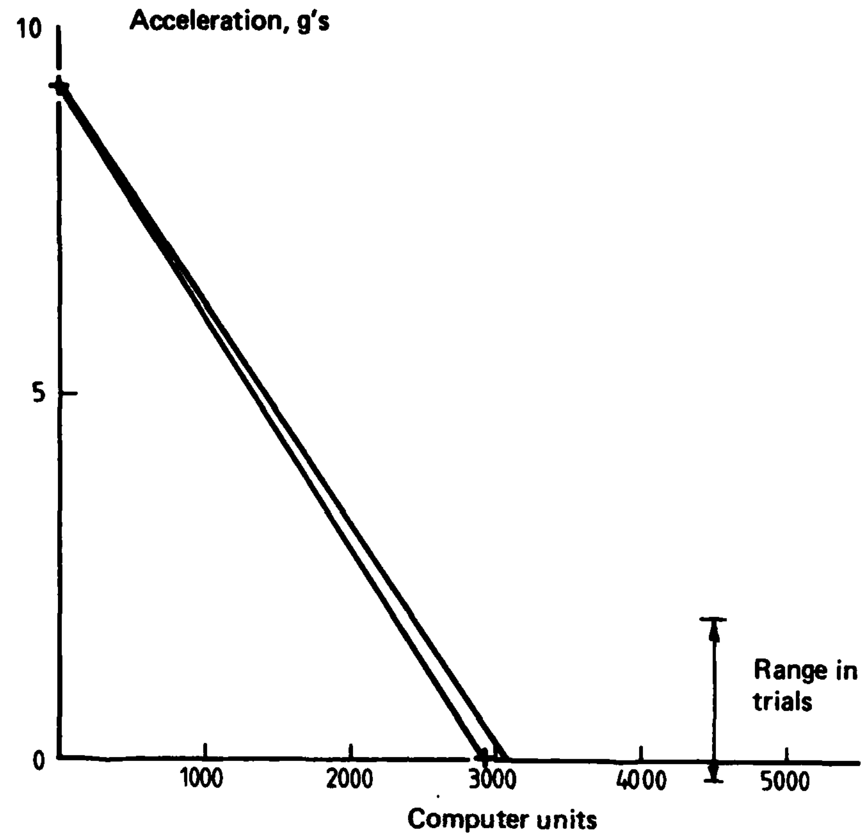

FIG. 3 NORMAL ACCELERATION CALIBRATIONS

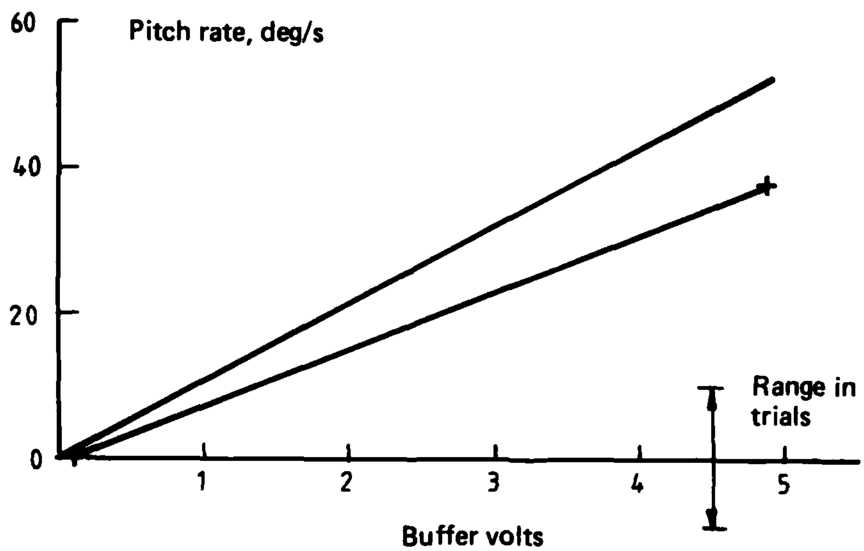

FIG. 4 PITCH RATE CALIBRATIONS

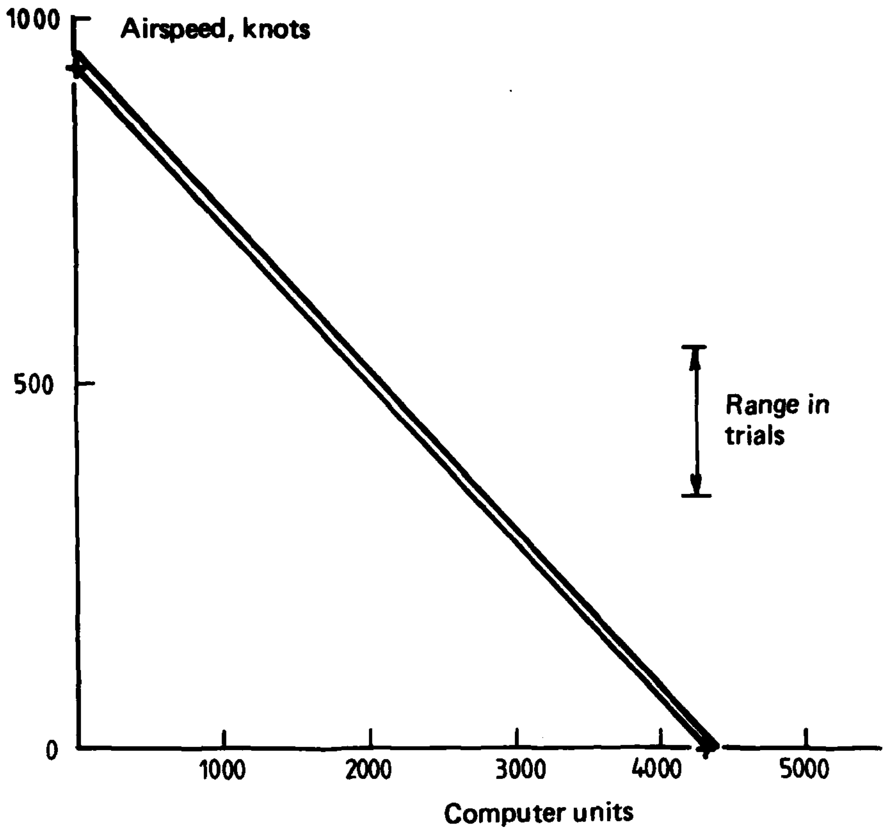

FIG. 5 AIRSPEED CALIBRATIONS

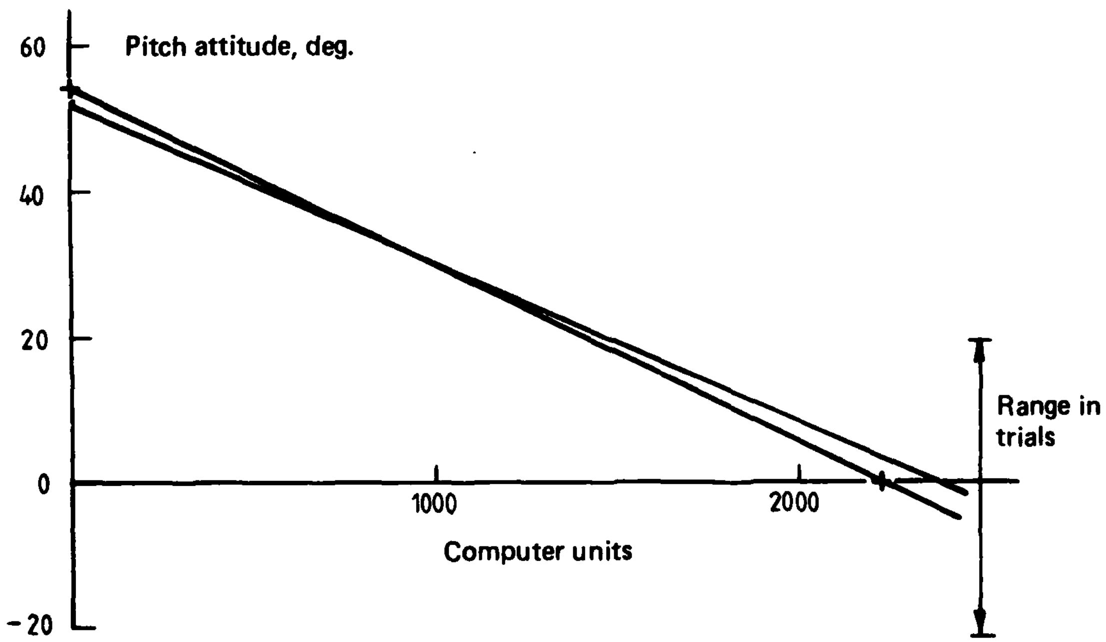

FIG. 6 PITCH ATTITUDE CALIBRATIONS

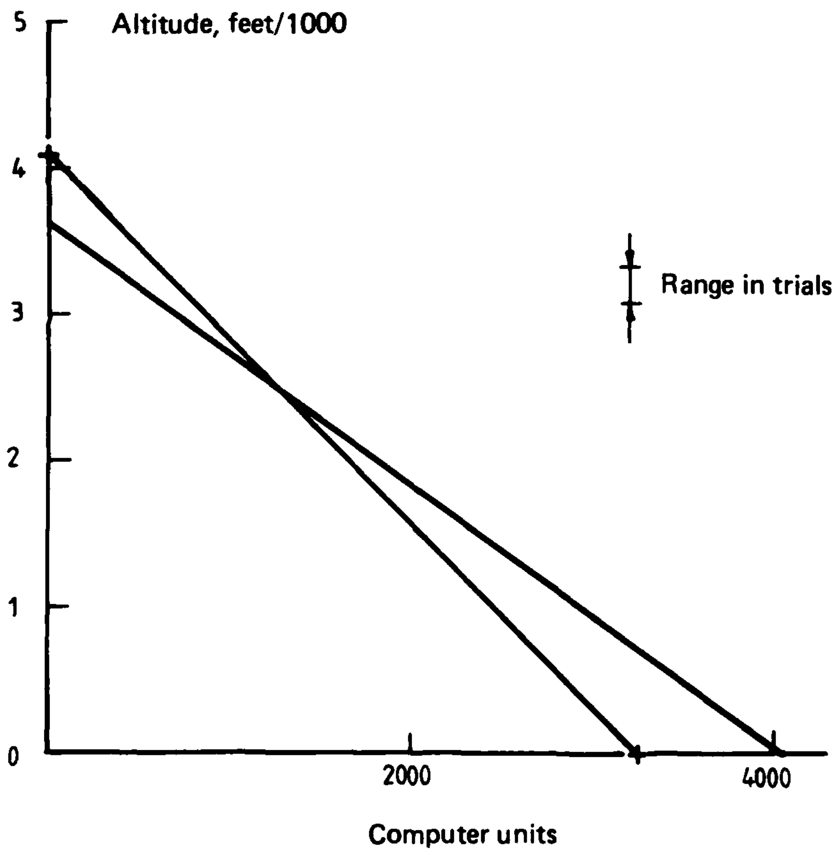

FIG. 7 ALTITUDE CALIBRATIONS

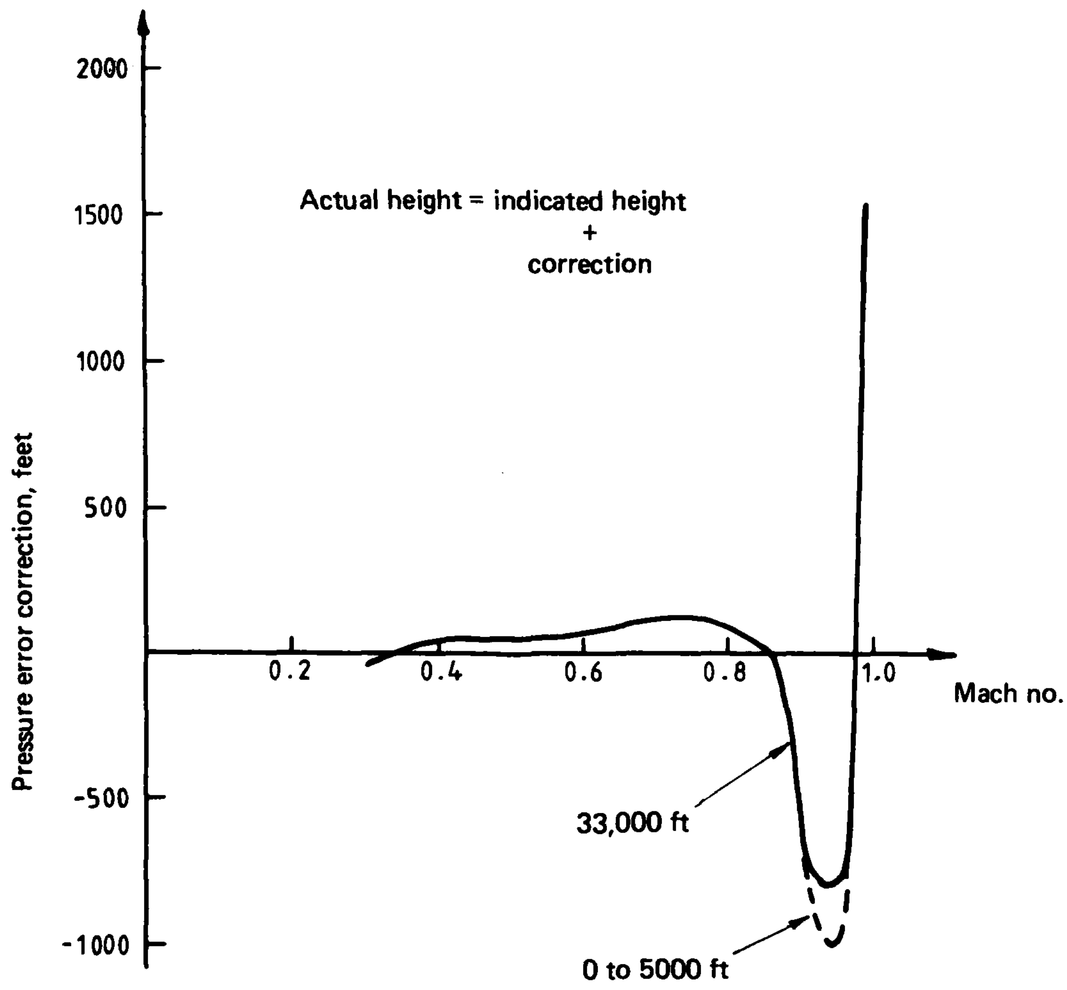

FIG. 8 PRESSURE ERROR CORRECTION FOR ALTITUDE

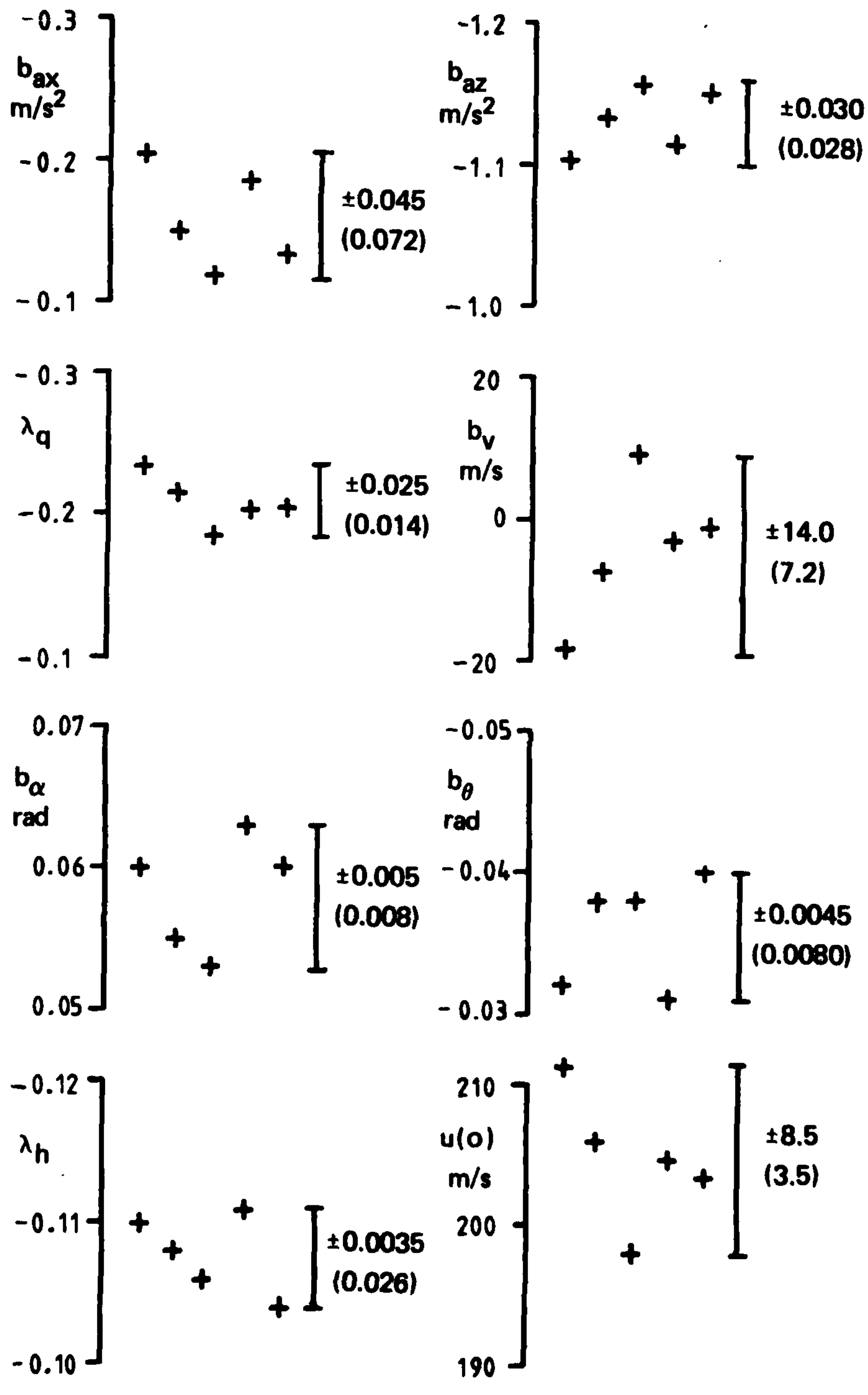

FIG. 9 SCATTER ON RESULTS – MANOEUVRE 1

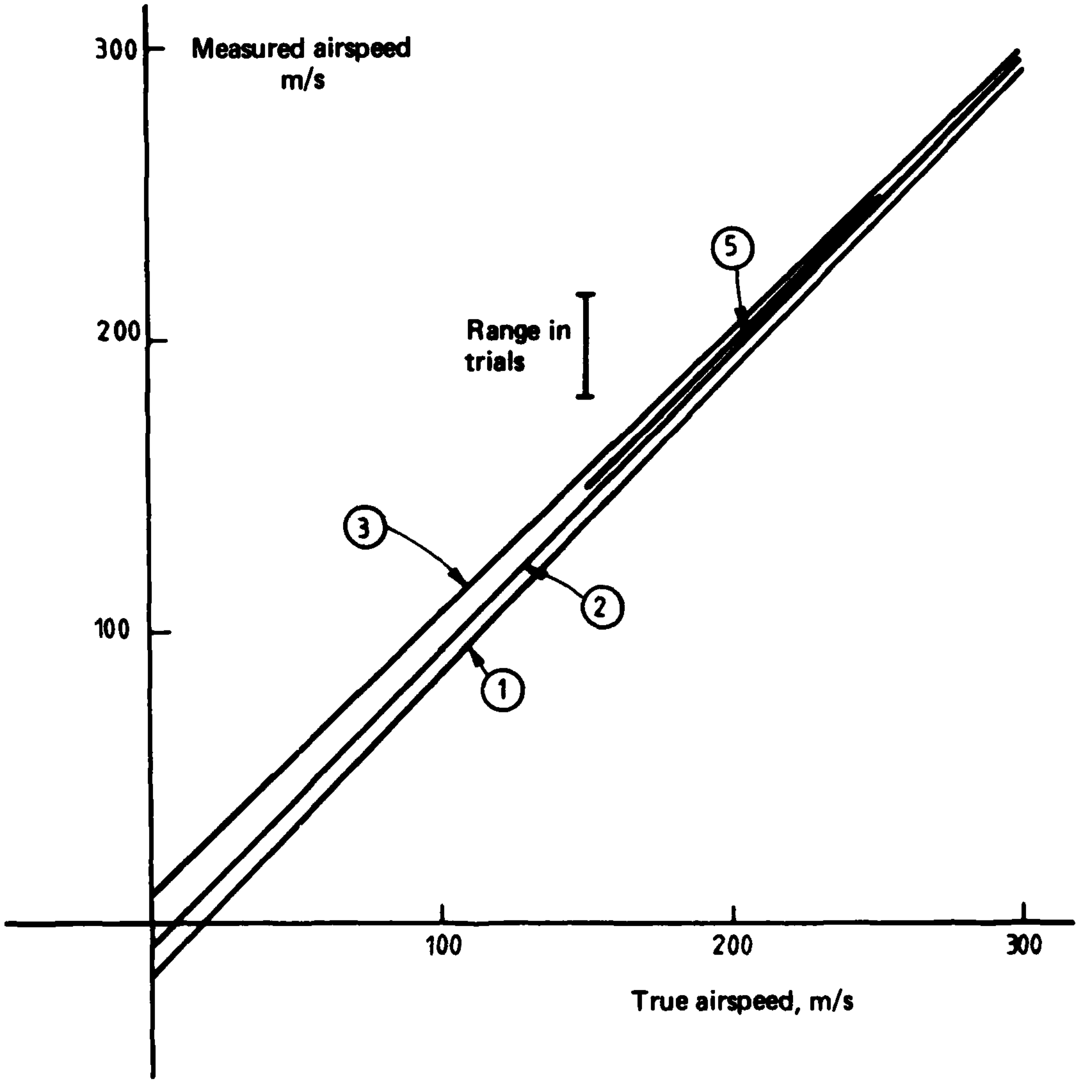

FIG. 10 VARIATIONS IN EXTRACTED AIRSPEED CALIBRATIONS -- MANOEUVRE 1

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Flight tests	Flight path reconstruction	
Data acquisition	Maximum likelihood estimates	
Estimation	Instrument errors	
Time lag		

16. Abstract

The considerable potential benefits of compatibility checking of aircraft dynamic flight data have in the past not been fully realised when applied to real data. It is suggested in this report that this is partly due to the presence of errors in the real data which are not usually accounted for in computer simulation studies. When factors such as accelerometer offset from centre of gravity, measurement time delays and other non-linearities are accounted for, good results can be achieved with moderate quality instrumentation. The effect of these factors on the identified instrument errors are studied in this report and confidence in the results established by a careful comparison with instrument calibrations and expected errors. Other considerations, such as the influence of manoeuvre shape and the inclusion of altitude record, are also discussed, and the conditions for successful application of compatibility checking techniques to flight data are summarised. The importance of understanding the instrumentation system is highlighted.

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17. Imprint Aeronautical Research Laboratories, Melbourne		
18. Document Series and Number Aerodynamics Report 162	19. Cost Code 517715	20. Type of Report and Period Covered
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